INTEGRATION OF CONTROL PROCESSORS IN THE REGIONAL SIMULATION MODEL (RSM)

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Abstract The Regional Simulation Model (RSM) incorporates an interchangeable suite of hydraulic control algorithms. RSM inputs are specified in the Extensible Markup Language (XML). The combination of standardized inputs, with interchangeable control processes enables a wide variety of control schemes with minimal overhead imposed on the modeler.

INTRODUCTION

The capability to accurately model anthropogenic water resource policies is an important aspect of many contemporary hydrological model applications. There are a wealth of advanced management techniques applied to water resource models, for example, linear programming, artificial neural networks, fuzzy control, dynamic programming, simulated annealing, genetic algorithms, and hybrids of all of these. However, such hydrological models tend to be specialized, not widely available, require non-standard input formats, and are limited in scope to either reservoir routing or local hydrological control. Alternatively, the majority of models which are widely accepted by the hydrological community are typically limited to rating curve expressions of control algorithms. Such expressions may not be sufficient for modern hydraulic control modeling. The Management Simulation Engine (MSE) component of the Regional Simulation Model (RSM) addresses this issue with the implicit integration of a suite of control algorithms including PID, PI-Sigmoid, linear transfer function, fuzzy rule-based, and arbitrary finite state-machine controllers. The controllers have transparent access to any state variable (hydrologic or control) through the use of a uniform data monitoring interface, and can be dynamically combined to create hybrid controllers.

Regional Simulation Model In the RSM, the Hydrologic Simulation Engine (HSE) provides hydrological and hydraulic state information (Σ), while operational policies dictate managerial constraints and objectives (Λ). In the MSE this state and process information can be functionally transformed or filtered by Assessors (A). The MSE then produces water management control signals (χ, μ) which are applied to the hydraulic control structures in order to satisfy the desired constraints and objectives. Figure 1 illustrates this overall cyclic flow of state and management information in the RSM.

The MSE architecture is based on a multilayered hierarchy, with individual water control structures regulated by 'controllers' while the regional coordination and interoperation of controllers is imposed by 'supervisors'. Supervisors can change the functional behavior of controllers, completely switch control algorithms for a structure, or override the controller output based on integrated state information and/or rules. A schematic depiction of the HSE-MSE layered hierarchy is shown in figure 2.

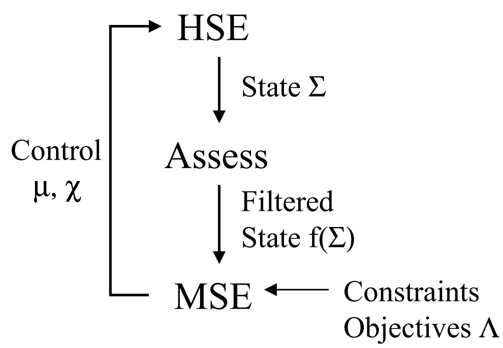

Figure 1: RSM state and management information flow

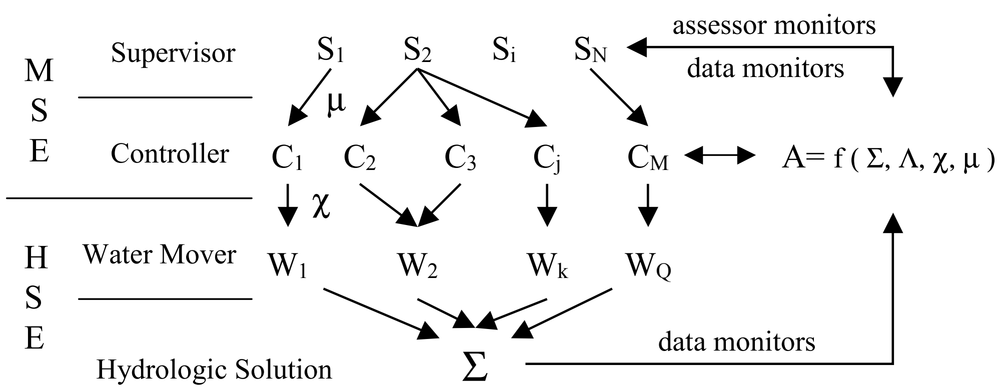

Figure 2: HSE MSE schematic

MSE CONTROLLERS

The MSE controller layer is the intermediary between the hydraulic structure watermovers and the regional-scale supervisory coordinators. The controllers can operate independently of the supervisors. The essential purpose of a controller is to regulate the maximum available flow through a structure to satisfy a local constraint. A controller may take as an input variable any state or process information which can be monitored within the RSM. Since the interface between a structure watermover and any controller is uniform, it is possible to change controllers dynamically with a supervisory command, or manually with a simple XML input change. The unitary interface also allows for the modeler to mix and match controllers in a particular model application so that the local control schemes are a hybridization of any of the available control algorithms.

The currently available controller modules in the RSM include:

- One & two dimensional rulecurves
- Piecewise linear transfer function
- Proportional Integral Derivative (PID) feedback control

- Sigmoid PI feedback control
- Fuzzy control
- User defined finite state machine

Each of these is briefly described in the following sections. Detailed information regarding the usage, applicability, and examples of model implementations are described in [SFWMD, 2004].

Example Geometry To provide illustrative examples of the controller applications, a sample geometry is defined using a simple canal network. A canal consisting of 4 segments is defined. Each segment is 100m wide, 3535m long, has a bottom elevation of 492m, and a lip height of 0.2m. The first and fourth segments are isolated from the network by junctionblocks. The first segment has a constant source, which adds a constant flow to the first segment. The fourth segment has a constant sink, which removes a constant flow from the fourth segment. Structure 1 (WM1) is attached to segment 1, and is controlled by the first controller. Structure 2 (WM2) is attached to segment 4, and is controlled by the second controller. The initial heads in the first and fourth segments are 505m, and 495m respectively. The objective of the controllers will be to regulate the structure flows to achieve a water level of 500m in the first and fourth segments. A schematic depiction of the network is shown in Figure 3. As a basis for comparison to controlled watermovers, Figure 3 shows the segment 1 and segment 4 response to the structures, sources and sinks, without any control exerted on the structures.

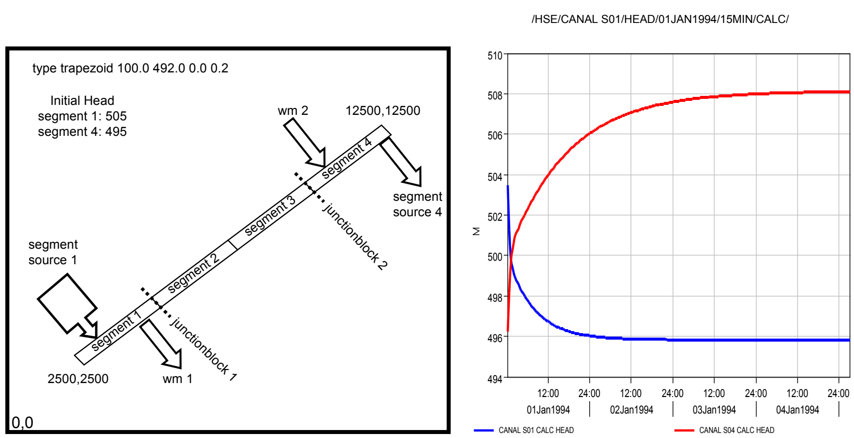

Figure 3: Controller Test Case and Uncontrolled Canal Segment Responses

One & two dimensional rulecurves Nearly all management enabled hydrologic models implement rulecurves in some fashion as a method of controlling the flow transfer function of hydraulic structures. The MSE provides for one or two variable interpolated lookup tables as a means of structure control. Notable in the MSE implementation is that the selected variables can be taken from any HSE or MSE variable which can be monitored, not just water level or flow variables.

Piecewise linear transfer function With the piecewise linear transfer function controller, the user specifies a control function as a combination of two or three linear segments as shown in figure 4. The upper and lower control values are C_H and C_L, with the control output determined by the value of the input state variable ϕ in relation to the upper and lower threshold values τ_H and τ_L. This controller can act as either a binary switch between the output control values of C_H and C_L, or can provide linear interpolation between the control points (τ_L, C_L) and (τ_H, C_H) along with lower and upper saturation values at C_L and C_H. The middle plot of figure 4 shows the test case control signals for the structures, the plot on the right shows the segment responses.

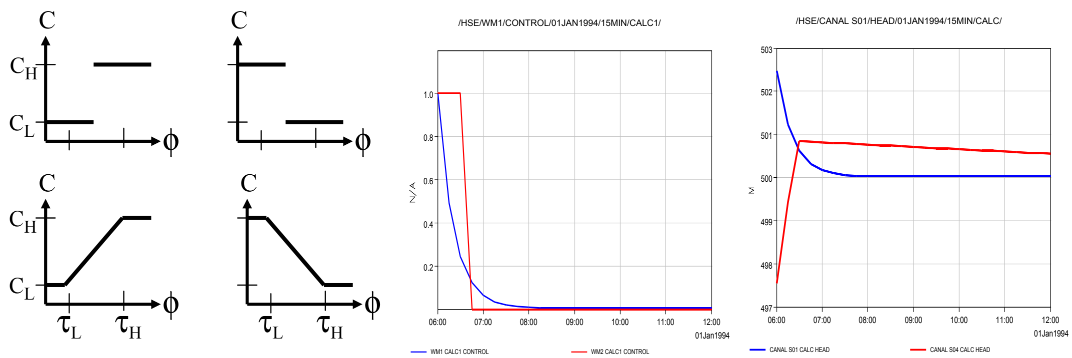

Figure 4: Piecewise linear transfer function schematic, control response, canal response.

Proportional Integral Derivative (PID) feedback control MSE implements a standard closed-loop feedback PID controller based on the time difference approximation

$$C(i) = \gamma_P \, \epsilon_i + \gamma_D \frac{\triangle \epsilon_i}{\triangle t} + \gamma_I \sum_{i=1}^{n} \epsilon_i \triangle t \tag{1}$$

where γ_P γ_D and γ_I represent gain factors for the proportional, derivative and integral terms, the system state variable to be controlled is $\phi(t)$ and the desired system target state is $T(t)$ at timestep t. The system error is computed as $\epsilon(t) = \phi(t) - T(t)$. The middle plot of figure 5 shows the test case control signals for the structures, the plot on the right shows the segment responses.

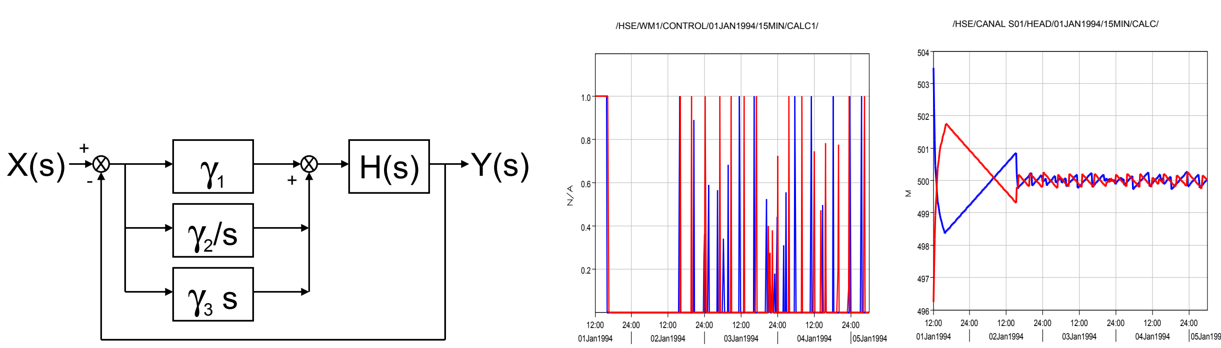

Figure 5: PID controller schematic, control response, canal response.

Sigmoid PI feedback control The sigmoid controller is essentially a PI controller with a single nonlinear activation function (the sigmoid) filtering the controller output. The PI portion of the controller is implemented as specified in equation 1 without the derivative term. Once a preliminary PI control output is available C_{PI}, the output is processed by a nonlinear sigmoidal activation function commonly known as the logistic or sigmoid function which is specified by

$$S(cx) = \frac{1}{1 + e^{-cx}}. \tag{2}$$

with $c > 0$. The value of c determines the slope of the activation function at the origin, and can change the functional behavior from that of a slowly rising transition (c$\rightarrow$0) to one of a unit step function ($c \rightarrow \infty$). This function serves to limit the possibly unbounded control outputs to the interval [0,1], while also providing an adjustable derivative for the linear portion of the activation function. Finally, the processed control signal is scaled by a constant scale factor α. The resultant sigmoid control signal is therefore given by

$$C(i) = \alpha\, S\left(C_{PI}(i)\right) \tag{3}$$

The sigmoid controller has been shown to increase stability and tolerance of closed loop feedback PI control to large variations of input state variables [Park, 2005].

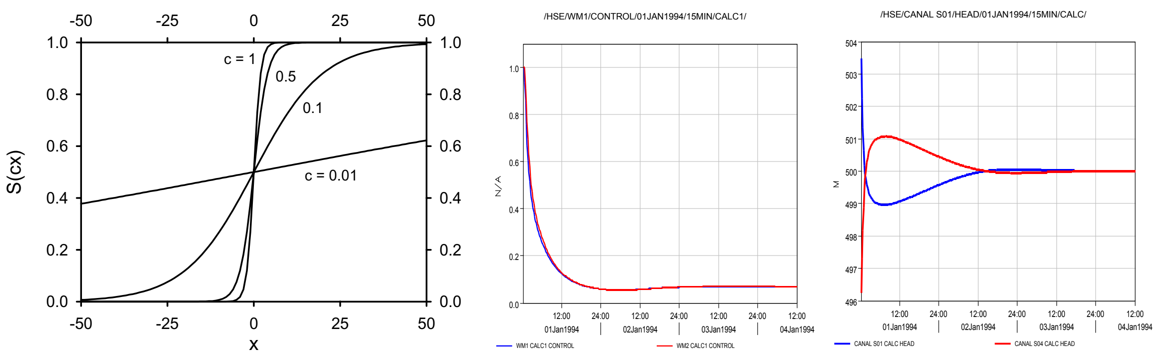

Figure 6: Sigmoid function, control response, canal response.

Fuzzy control The MSE incorporates a generic fuzzy controller as defined by the International Electrotechnical Commission (IEC) standard for Fuzzy Control Programming [IEC, 1997]. The fuzzy controller constitutes a rule-based expert system utilizing an inferencing engine coupled with multiple constraint aggregation. Fuzzy control can be useful in cases where there exists an experiential reference base that can be expressed in terms of rules. In contradiction to many canonical control processors, fuzzy control doesn't require knowledge of the system transfer function, that the transfer function be expressible in closed form, or that the system has to be linear. An additional advantage is that the rule base is expressed in a linguistically natural format and can be easily understood by non-specialists.

The definition of a fuzzy controller is expressed in the Fuzzy Control Language (FCL) [IEC, 1997]. The FCL specifies the input/output variables, fuzzy membership functions, and rule-base. The fuzzy controller supports five types of input/output terms for fuzzification and defuzzification illustrated in figure 7.

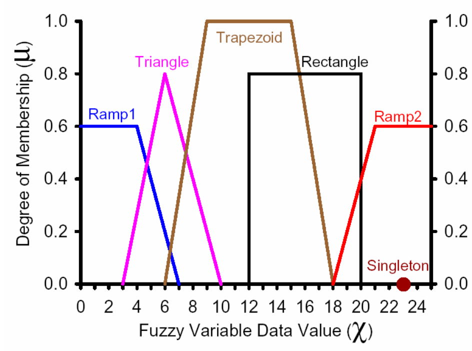

Figure 7: MSE fuzzy I/O terms

An example FCL excerpt for the fuzzy controller is shown below.

```
FUNCTION_BLOCK Fuzzy_Controller
VAR_INPUT
        segment1Head : REAL;
        segment4Head : REAL;
END_VAR
VAR_OUTPUT
        control1Out : REAL;
END_VAR
FUZZIFY segment1Head
        TERM low  := (499, 1) (500, 0);
        TERM med  := (498, 0) (499, 1) (501, 1) (502, 0);
        TERM high := (500, 0) (501, 1);
END_FUZZIFY
FUZZIFY segment4Head
        TERM low  := (499, 1) (500, 0);
        TERM med  := (498, 0) (499, 1) (501, 1) (502, 0);
        TERM high := (500, 0) (501, 1);
END_FUZZIFY
DEFUZZIFY control1Out
          TERM zero  := 0.;
          TERM half  := 0.5;
          TERM one   := 1.;
END_DEFUZZIFY
RULEBLOCK No1
          RULE 1: IF segment1Head IS low  THEN control1Out IS zero;
          RULE 2: IF segment1Head IS med  THEN control1Out IS half;
          RULE 3: IF segment1Head IS high THEN control1Out IS one;
          RULE 4: IF segment4Head IS low  THEN control1Out IS one;
          RULE 5: IF segment4Head IS med  THEN control1Out IS half;
          RULE 6: IF segment4Head IS high THEN control1Out IS zero;
END_RULEBLOCK
END_FUNCTION_BLOCK
```

User defined finite state machine In certain cases, a canonical fixed transfer function or rule-based expert system controller may not best suit the needs of a hydraulic structure watermover controller. To accommodate this, the MSE allows the user to develop arbitrary

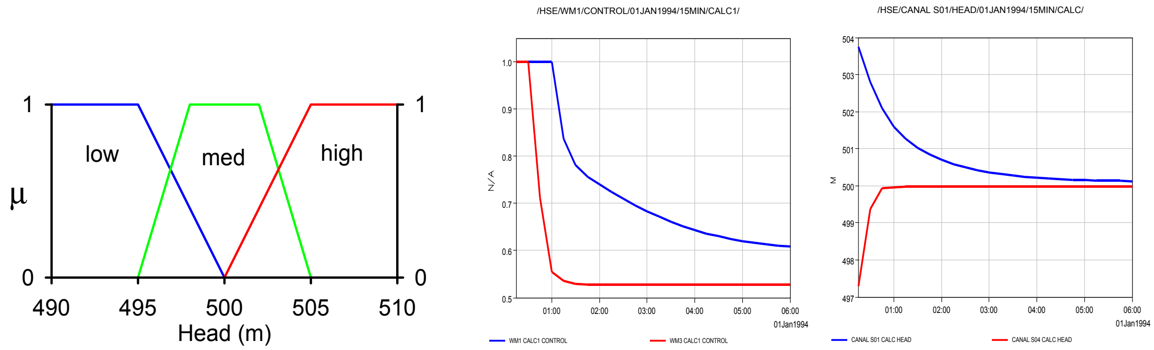

Figure 8: Fuzzy input terms, control response, canal response.

finite state machine algorithms through the development of C or C++ shared libraries. MSE implements a dynamic shared library loader and function pointer interface which calls the user defined control function(s) at each timestep. Each controller maintains it's own shared object and function pointer information, allowing the user to define multiple control functions inside a single shared object. The control functions can receive multiple input state variables from any data source that can be monitored within the RSM. The input-output interface to the user functions are detailed in [SFWMD, 2004]. An excerpt of C++ code for the example controllers is shown below.

```
extern "C" double Segment1_Control( map<string, InputState*> *lpInput ) {
  double controlOut   = 0.;
  double segment1Head = GetVarIn( "Segment1", lpInput );

  // Provide control function based on input state variable
  if ( segment1Head > 502. )          controlOut = 1.;
  else if ( segment1Head > 501. )    controlOut = 0.5;
  else if ( segment1Head > 500. )    controlOut = 0.2;
  else                               controlOut = 0.;

  return controlOut;
}
```

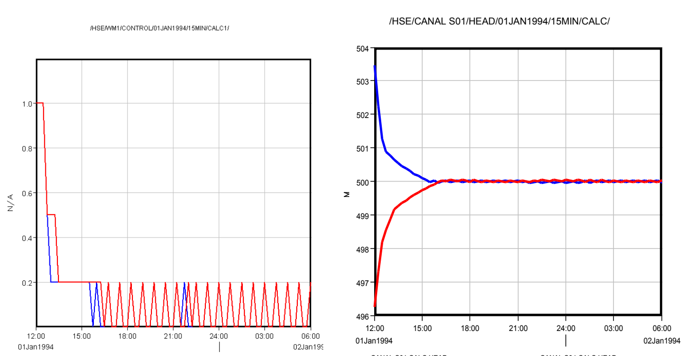

Figure 9: User defined controller response, canal response.

CONCLUSION

The Regional Simulation Model incorporates a diverse suite of structure control algorithms encompassing contemporary control processors in a generalized fashion. The control algorithms and parameters are expressible in a model independent manner, that is, the controllers are expressed purely through standardized model inputs such as XML, C++, FCL, so that no structural changes (recompilation) of the RSM executable is required to implement different controllers. The controllers are able to access any model hydrological, time event, or process control variable through the use of a common data monitor interface. Further, the controllers are interfaced to the model hydraulic structures through a common interface. This allows interoperability and exchangeability between any of the controllers, thereby enabling the implementation of dynamic hybrid controllers.

References

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[IEC, 1997] International Electrotechnical Commission (IEC), Technical Committee No. 65, Industrial Process Measurement and Control Sub-committee 65B: Devices, IEC 1131 - Programmable Controllers, 1997 Part 7 - Fuzzy Control Programming